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FEASIBILITY OF MINIATURIZED INSTRUMENTATION OF THE INFLATABLE SPHERE FOR TEMPERATURE, PRESSURE AND ACCELERATION MEASUREMENT

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16. Abstract

The feasibility of instrumenting the inflatable passive sphere (presently used to provide upper atmosphere density measurements) with miniaturized thermistors, pressure transducers and accelerometers has been analyzed. Data from the sensors must be transmitted by an onboard telemetry system to a ground receiving station. To assure a sufficiently slow fall velocity for the sphere the additional mass of the sensor and telemetry hardware must be less than 100 grams. Other constraints that must be satisfied by the sensor and telemetry systems include the ability to withstand a 150 g launch acceleration, the ability to function in both high and low temperature and pressure environments and be sufficiently small to be packaged within the body of a 3.81 cm diameter dart. The feasibility study concludes that temperature and acceleration sensors can be found, and a two channel telemetry system designed that will perform satisfactorily. The performance of an absolute pressure transducer is doubtful due to the large range of pressure that will be experienced. A differential transducer that will measure the difference between ambient and internal sphere pressures appears practical. The application of each type of measurement relative to its ability to monitor sphere malfunction and to provide additional meteorological data is also considered. The development and firing of several experimental systems has been recommended.

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TABLE OF CONTENTS

FEASIBILITY OF MINIATURIZED INSTRUMENTATION OF THE INFLATABLE SPHERE FOR TEMPERATURE, PRESSURE AND ACCELERATION MEASUREMENT

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SUMMARY

The feasibility of instrumenting the Robin sphere with miniaturized thermistors, pressure transducers and accelerometers has been studied and it appears practical to proceed with an experimental test program. Skin temperature is the most important of the three parameters and highest priority should be allotted toward incorporating it into the Robin system. Skin temperature measurements could potentially be used to calculate temperature, pressure, density, and vertical winds from 90 through 30 Km.

A pressure measurement would primarily be used as a diagnostic tool in monitoring the inflation-collapse behavior of the sphere. The technical feasibility of a pressure transducer accurately monitoring internal sphere pressure has not been completely established. It does however appear justified in pursuing on a limited experimental basis. Its need, potential and cost however do not warrant the emphasis in a developmental program that should be given the temperature measurement.

The technical feasibility for acceleration measurements is quite favorable. The application of the acceleration measurement however may be limited if the orientation of the sphere is not sufficiently stable to produce a steady state acceleration trace. If the total drag acceleration can be accurately deduced from a single axis accelerometer then the passive sphere system could be utilized at locations not possessing an FPS-16 radar.

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SECTION 1
INTRODUCTION

Over the past ten years the Robin System has provided a low cost method of obtaining upper atmospheric measurements of winds, temperature, density and pressure. The mid sixties saw a one meter corner reflector sphere carried aloft by an Arcas rocket provide measurements between 30 and 60 Km (ref. 1). Questionable accuracy in the drag table and hardware reliability problems proved a noteworthy obstacle to a general acceptance of the inherent accuracy of the passive sphere system.

The general need for the passive sphere system was supplanted with the development of the Datasonde system. After a lengthy period of controversy concerning heating correction terms the Datasonde system now provides accurate temperature profiles by use of a bead thermistor to 60 Km. Due to the magnitude of heating corrections that must be applied to the bead thermistor at higher altitudes the potentially effective range of the Datasonde system is on the order of 65 Km. Above this altitude only the spheres and grenades systems are capable of providing accurate upper atmospheric parameters on an operations basis. The grenade technique, however, requires a manyfold increase in cost over the sphere system and is no longer flown operationally.

The experience gained in the early development of the Arcas-Robin program led naturally to the development of a high altitude sphere system designed to provide meteorological parameters up to 100 Km (ref. 2). Originally a Viper Rocket motor was used to produce the thrust necessary to achieve the desired 125 Km apogee (ref. 3). After several years of service the Viper Rocket was replaced by a lower cost Super Loki motor. The Super Loki consisted of a Loki motor with a non-powered, low drag, second stage dart. After burnout the low drag dart separates fromthe Loki and continues upward to an apogee of nearly 115 Km. Here the sphere ejects from the dart body and is tracked by radar until collapse. This rocket system is still in operation.

The past five years saw changes in the sphere as well as the rocket vehicle. Like the Arcas and Viper systems the Super Loki system reliability was such that it provided accurate meteorological data down to 30 Km for only about 50% of the launches. Non-inflation and premature collapse of the sphere were major causes of system failure. Sphere changes were made to improve the overall reliability of the system. The first change in the sphere was the removal of the radar reflective corner reflector. To maintain radar tracking capability the sphere was metalized. The metalized spheres provided accurate radar tracking and in addition lightened the sphere mass by 20 grams. Unfortunately the reliability and inflation-collapse problems of the sphere did not disappear. Next a pyrotechnic time delay was introduced into the inflation capsule. It was speculated that immediate inflation of the sphere at ejection was causing it to rupture. The burden of a time delay capsule increased the sphere mass by 70 grams without solving the problem. Next it was suggested that aerodynamic heating of the dart body was causing fusion of the mylar and preventing proper inflation at ejection. A thermal insulation coating was sprayed on the dart body for protection. The insulation proved helpful in some situations but did not resolve the inflation-collapse problem. The next speculation was that due to insufficient heat the isopentane was not fully vaporizing and the result was early sphere collapse. Consequently cisbutane-2 was substituted for isopentane. The results were again negative. In nearly all of the above system modifications temporary improvement in system reliability resulted but subsequent shipments of production systems reverted back to the previous problems.

As a result of the problems still associated with the passive sphere system a feasibility study has been undertaken to assess the use of miniaturized sensors attached to the sphere as a means of monitoring the sphere behavior. The specific purposes of the feasibility study are threefold; to gain knowledge concerning causes of sphere failure, to provide data that can substantiate or improve measurement accuracies as calculated from the Data Reduction Program and to improve the system either through the measurement of parameters previously not measured, or through more accurate measurement of the parameters presently obtained from the radar coordinates.

The study considers the use of miniaturized temperature sensors, pressure transducers and accelerometers with the accompanying telemetry hardware needed to transmit the data to a ground receiving station. The inherent value of each type of measurement and the particular instrumentation problems associated with obtaining it are discussed in Sections 2, 3, and 4. In addition to the unique constraints and environmental qualifications associated with a thermistor, pressure transducer or accelerometer there are overall system constraints inherent in the Viper Dart or Super Loki systems. The system constraints are as follows:

1. All telemetry and sensors must withstand 150 g launch forces.
2. Volume of sensors, battery and telemetry hardware must not exceed 100 cubic centimeters.
3. To fit inside the dart body a diameter of the instrument sensor package must be less than 2.5 centimeters.
4. Increased mass of sphere due to instrumentation must be less than 100 grams.
5. Instrumentation must monitor sphere behavior for the duration of a flight (approximately 20 minutes).

Under these constraints and subject to the environmental atmospheric extremes of temperature and pressure three types of onboard measurement sensors were evaluated; internal pressure, skin temperature, and acceleration.

SECTION 2
SKIN TEMPERATURE

The measurement of the skin temperature of the sphere would be desirable for several reasons. At separation of the sphere from the rocket body the isopentane capsule is ruptured and inflation begins. The heat required to vaporize the isopentane comes from the skin and the capsule. If sufficient radiant and aerodynamic heating is lacking to raise the temperature of the gas above the boiling point of isopentane then not all isopentane will vaporize and the pressure inside the sphere will be the vapor pressure of isopentane corresponding to the sphere temperature. Since the boiling point of isopentane at 10 mb pressure is approximately 210°K, sphere temperatures lower than this could cause only partial inflation or premature collapse. A monitor of skin temperature can be used to determine when vaporization of the isopentane is complete, or if the skin temperature becomes excessively cold and vaporization ceases or condensation occurs.

A second use of skin temperature measurements concerns the effect of skin temperature on the drag coefficient at Mach numbers greater than 1. Figures 1 and 2 from Bailey and Hyatt 1971 (ref. 4) show the influence of skin (wall) temperature to be largest at low reynolds numbers. To measure the change in density that would result if a skin temperature correction were used in the Robin program to calculate density a simulation procedure was initiated.

The theoretical path of a passive sphere falling through the 1962 Standard Atmosphere was generated. The space time position coordinates were then used as input to the Robin program and a density and temperature profile generated. Next the Robin program was modified to include the skin temperature effect on drag coefficient. Three skin temperatures versus altitude profiles were designated as the input. The density profiles produced by the modified Robin program using the skin temperature profiles

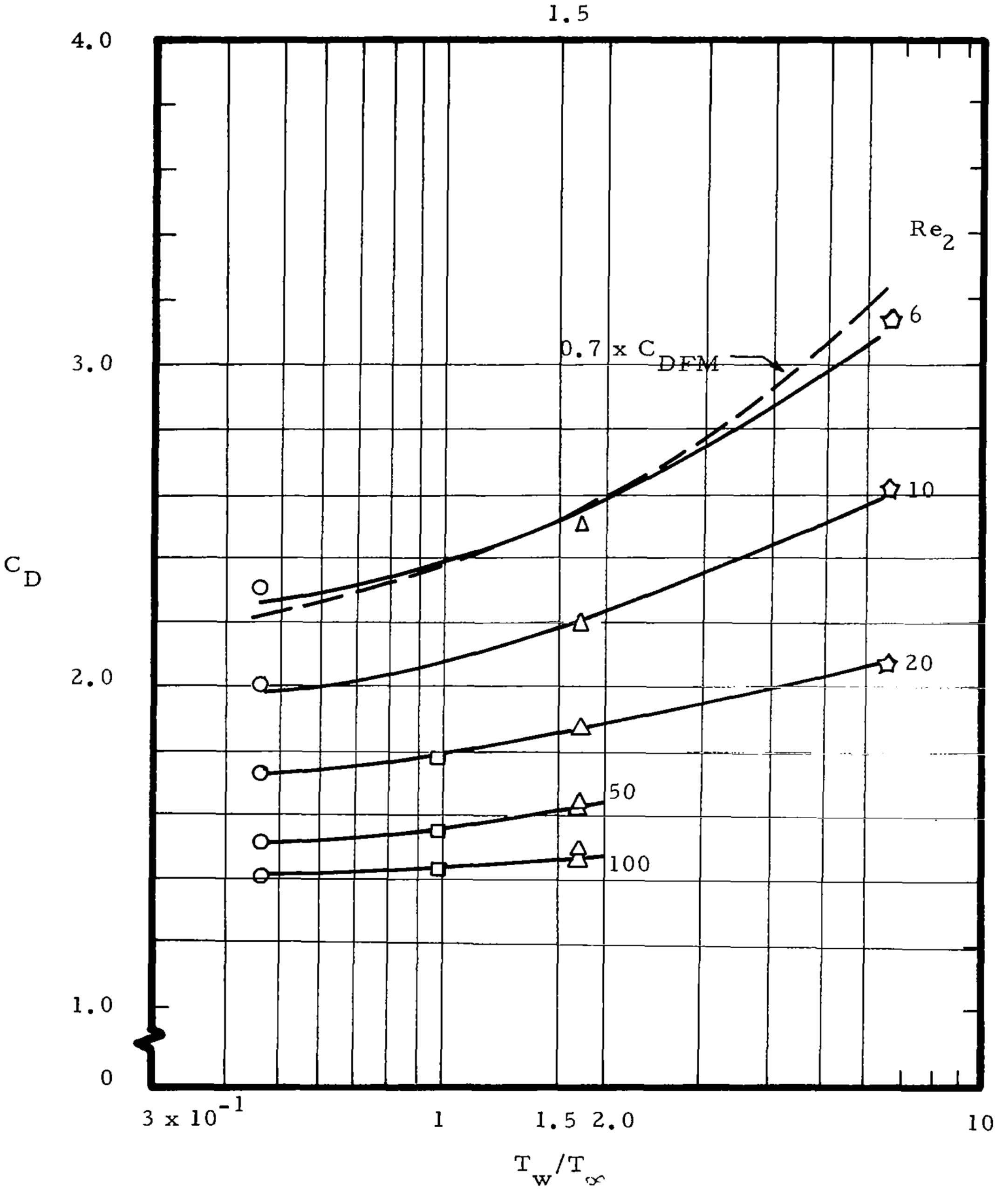

Figure 1. Variation of Sphere Drag Coefficient with Wall Temperature at Mach 2.0 (Ref. 4)

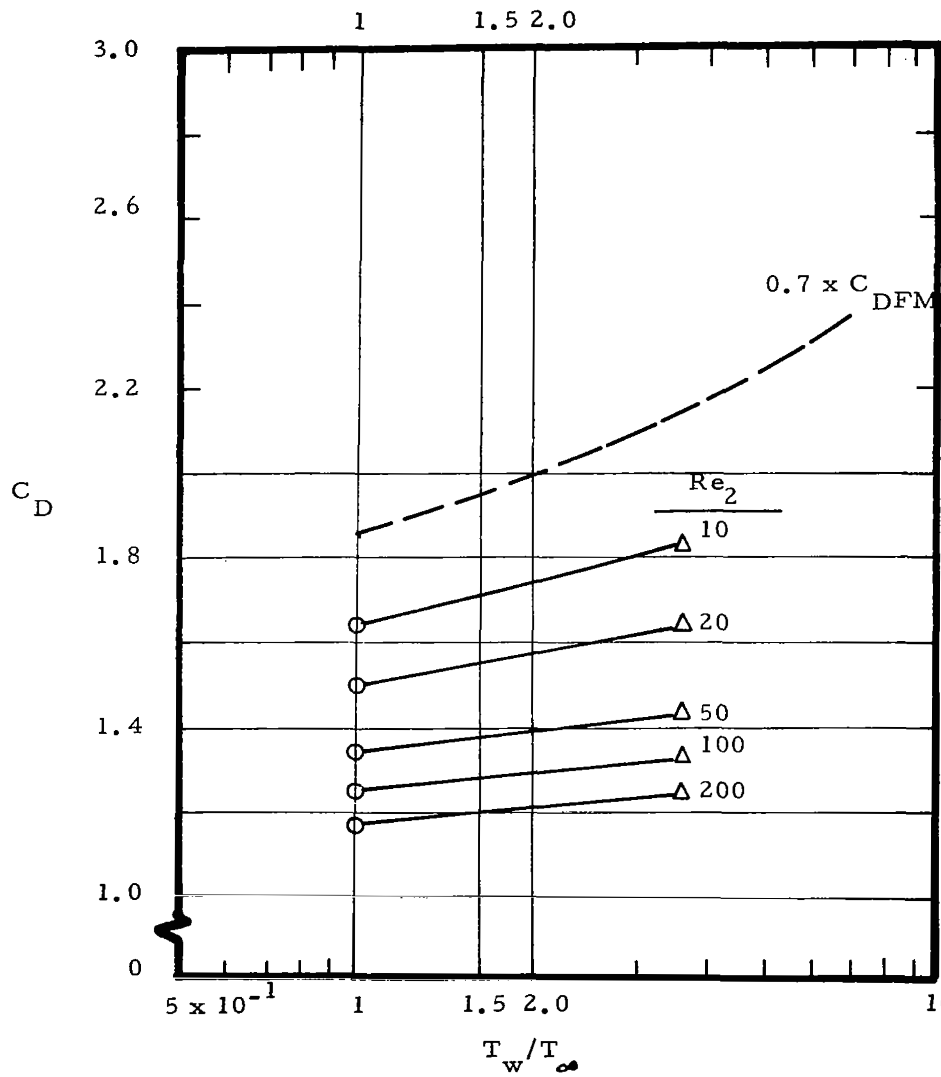

Figure 2. Variation of Sphere Drag Coefficient with Wall Temperature at Mach 3.0 (Ref. 4)

was compared to that from the original Robin program to determine the influence of skin temperature.

Figure 3 shows the three skin temperature profiles used. (1962 Standard Atmosphere profile is also shown). The Australian profile was actually measured with the Australian two meter sphere by an onboard thermistor. The maximum and minimum heating profiles were defined as the two extremes of skin temperature profiles that could conceivably occur with the Robin system. The results of the simulation using these three input profiles is shown in Figure 4. This figure shows the change in density resulting from including the effect of skin temperature on C_D. The Australian profile shows less than 3% change in density from 90 to 100 Km and less than 2% below 90 Km. The minimum heating profile shows less change than the Australian profile. The maximum heating profile shows a change of 7% at the first data point (97.5 Km) but quickly decreases to 3% to 4% between 95 Km and 75 Km. At approximately 72 Km the Mach number becomes less than 1 and the skin temperature effect disappears. Since the maximum and minimum heating profiles are extreme situations actual flight conditions are expected to produce a smaller skin temperature influence. A monitor of skin temperatures onboard the Robin sphere would result in improved density accuracy of from 1-4% above 90 kilometers with insignificant improvement below this altitude.

A third benefit from skin temperature measurements would be the potential for calculating ambient atmospheric temperature (from skin temperature) after correcting for the radiant and aerodynamic heating of the sphere. At altitudes below 60 Km the fall rate and orientation of the sphere should be sufficiently stable to satisfactorily perform these calculations. Above 60 Km aerodynamic heating may be large. The accuracy to which both the radiant and aerodynamic heating corrections can be calculated are the limiting factors for providing a reliable measure of ambient temperature. To calculate the aerodynamic heating an accurate profile of sphere velocity, drag measured density

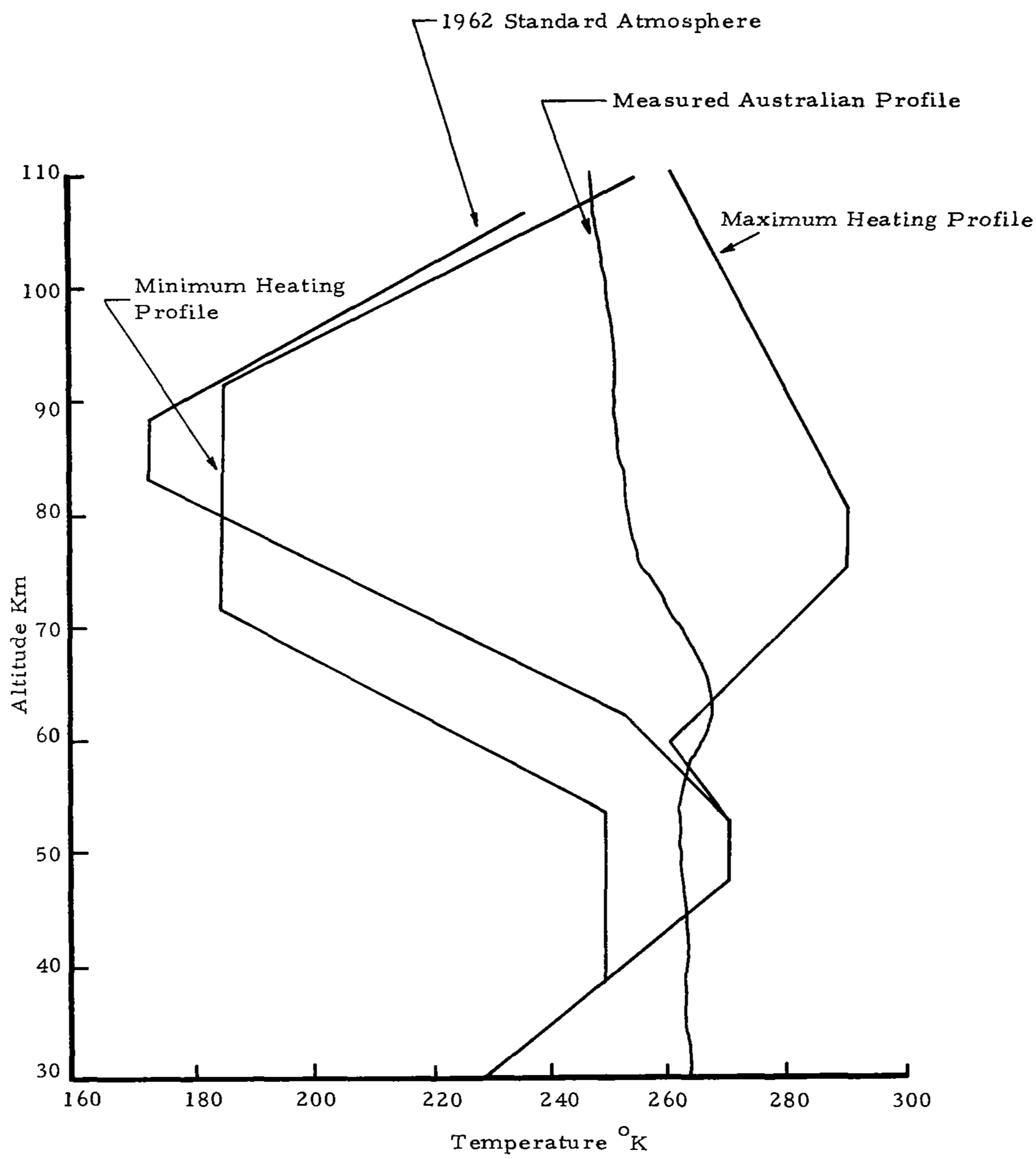

Figure 3. Measured and Hypothetical Skin Temperature Profiles

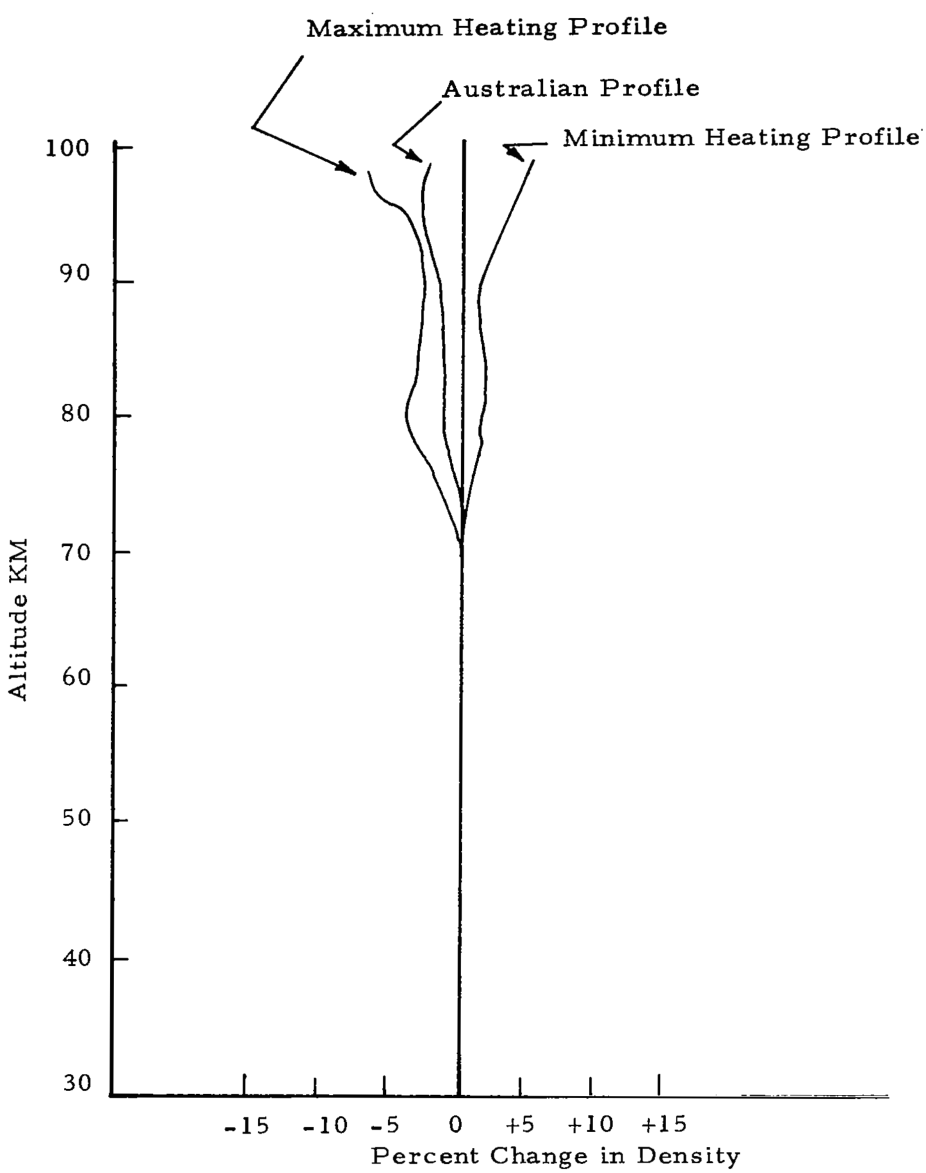

Figure 4. Change in Density When Skin Temperature Included

and sphere orientation is necessary and can be obtained through processing of the Radar tracking data. The radiant heat correction can be derived from absorptivity and emissivity properties of the aluminized mylar skin and the orientation of the sphere relative to the sun. By imbedding several thermistors at various locations within the skin the total heat content of the skin could be estimated and a mean skin temperature deduced. Experimental verification of the aerodynamic and radiant heat correction terms could be achieved by comparison of the corrected skin temperature to the ambient temperature derived from independent sources such as grenades, datasondes, and drag derived temperature from the sphere.

The development of an instrumented passive sphere system that provides direct temperature measurements from skin thermistors as well as a drag-measured density and temperature profile would be of enormous benefit to the meteorological community. Its adaptation would provide improved measurements of density, temperature, and winds from above 80 Km to 30 Km. In addition reliable estimates of vertical wind motions between 60 and 30 Km could be derived by attributing the difference between thermistor derived and drag derived temperatures to vertical winds. The system would also alleviate two shortcomings of the present passive sphere system: drag table inaccuracies and determination of collapse altitude. Temperature redundancy provides a means of verifying or correcting the drag table. Sphere collapse altitude should be identifiable through telemetry dropouts due to antenna disorientation when the sphere collapses. Such a system as described above would replace the need for the present Datasonde system. It would provide all of the data presently available from this system, with commensurate accuracy, and at the same approximate cost.

2.1 SENSOR REQUIREMENTS

The value of a skin temperature measurement is predicated upon the ability to measure temperature with a high degree of accuracy. For the applications discussed above skin temperature accuracy of 1 or 2 degrees celsius should suffice. The range of temperatures anticipated on the skin of the sphere are from $-60^{\circ}C$ to $+30^{\circ}C$. The choice of a temperature sensing device must satisfy these accuracy and range requirements. There are several commercial thermistor type sensing devices that meet these requirements. The Australian skin temperature sensing experiments used off the shelf type thermistors. They performed satisfactorily, are very light in weight - less than a gram - and provided good accuracy.

2.2 CIRCUITRY

The temperature thermistors must be incorporated into a circuit that fulfills the five system constraints delineated in Section 1. If more than two thermistors are used to sense temperature some type of signal multiplexing is needed. At present it appears that the mass of such a system would exceed the 100 gram limit. For this reason only two thermistors have been incorporated into the circuit.

Figure 5 shows a wiring schematic for the thermistor telemetry circuit. The circuit is nearly identical to the Australian circuit (ref. 5) with only minor modification primarily designed to transmit at a higher frequency.

A 15 volt D.C. battery would supply power to the circuit. A voltage regulator will maintain a constant 4.8 voltage to the pulse generation and shaping circuits. A silicon controlled rectifier and charging capacitor are used to convert DC to a pulsed output. The T1 thermistor signal varies the pulse rate. The T2 thermistor signal varies the duration of the pulses. The T1 and T2 signals are broadcast as a pulse train from a simple RF oscillator. Failure of either thermistor should not influence the performance of the other. A transistor is used to produce the desired 2200M Hertz frequency

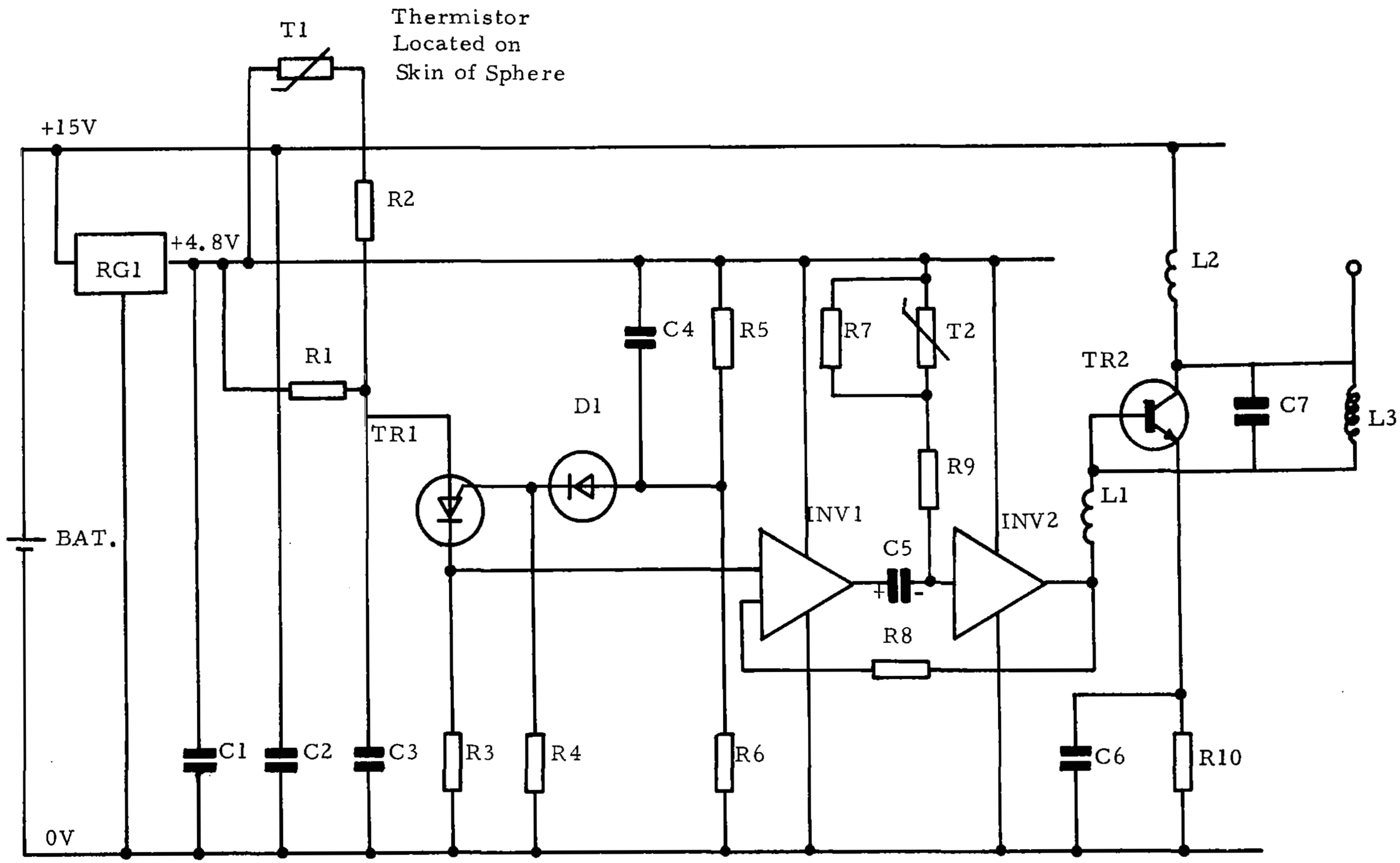

Figure 5. Circuit Diagram for Two Temperature Measurements

and transmit through a 1-1/4 wavelength antenna to a ground receiver.

The circuit will require approximately the following number of major components. Their mass and estimated cost is also included.

Units	Component	Mass	Est Cost (unit)
1	Battery	(39/64 x 19/32 x 1-3/8) 17g	\$2
3	Transistors (Oscillators)	1.2g	\$3
10	Precision Resistors	.35g	\$2
3	Integrated Circuit	1.0g	\$4
2	Thermistors	.5g	\$2
7	Capacitors	.5g	\$1
1	Switch	2.0g	\$2
3	Inductors	5.0g	\$3
6	Fiberglas Boards	.9g	\$1
4	Structural Supports	.6g	\$1
1	Antenna	2.0g	\$1
	Miscellaneous (Wire, Insulation, Cement etc)	15g	\$20

The total mass of the system would be on the order of 70-80 grams and certainly less than the design limitation of 100 grams. The approximate cost of materials alone would be \$100. The pressure sensing and acceleration sensings circuits will vary little in mass from the thermistor circuit but will increase in cost. This is further discussed in a later section.

2.3 PACKAGING

The circuit diagram shown in Figure 5 would be wired on six circular etched copper fiberglass base boards. The diameter of the boards would be approximately 2.54 cm so as to fit inside the dart body. The boards would be connected by cement to rigid fiberglass pins as shown in Figure 6. The entire structure can be potted with plastic foam to prevent damage and insulate the instrumentation from shock and temperature variations during launch. The two thermistors would be placed at different locations on the sphere. Our initial thought is that the two best locations may be at the leading point during descent, and at a position 90° around the sphere from the leading point. The location of the center of gravity (Cg), determines the leading point of the sphere and should approximately coincide with the location of the instrument package (See Figure 7). The antenna must be attached to the skin to remain in an orientation favorable to the ground receiving station. The Australian system replaced two metalized gores with transparent gores, cemented the antenna to one of these gores and placed the gores 180° apart around the sphere. With such an orientation, telemetry linkup was satisfactory. Occasional signal dropouts when the antenna was shielded from view enabled the spin rate of the sphere to be deduced without significant errors in reconstruction of the signal. The sphere could be designed similar to the Australian system by imbedding one of two transparent Mylar gores with an antenna. The antenna length will be considerably smaller for the sphere since transmission will be at a higher frequency.

The Viper Dart system contains an inflation capsule that is free to move about in the sphere during descent. The orientation of the sphere with respect to the leading point cannot be determined prior to launch. This knowledge is necessary so that the thermistor can be located at the proper positions on the sphere. The system can be improved by affixing the capsule to the skin to prevent internal motion of the capsule. The instrumentation package can be attached to one end of the capsule and the Cg location predetermined. A technique will be needed to activate the instrumentation after launch or at ejection. This can be accomplished by a mechanically activated or pressure sensitive switch.

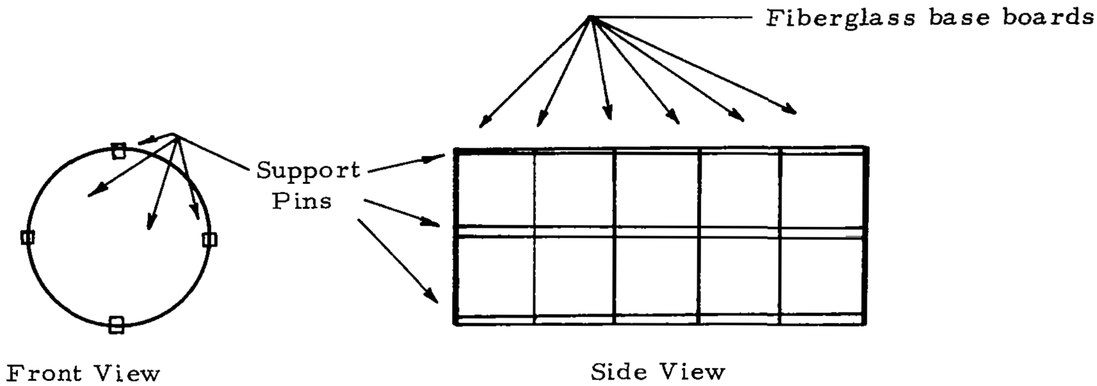

Figure 6. Instrumentation Circuit Boards

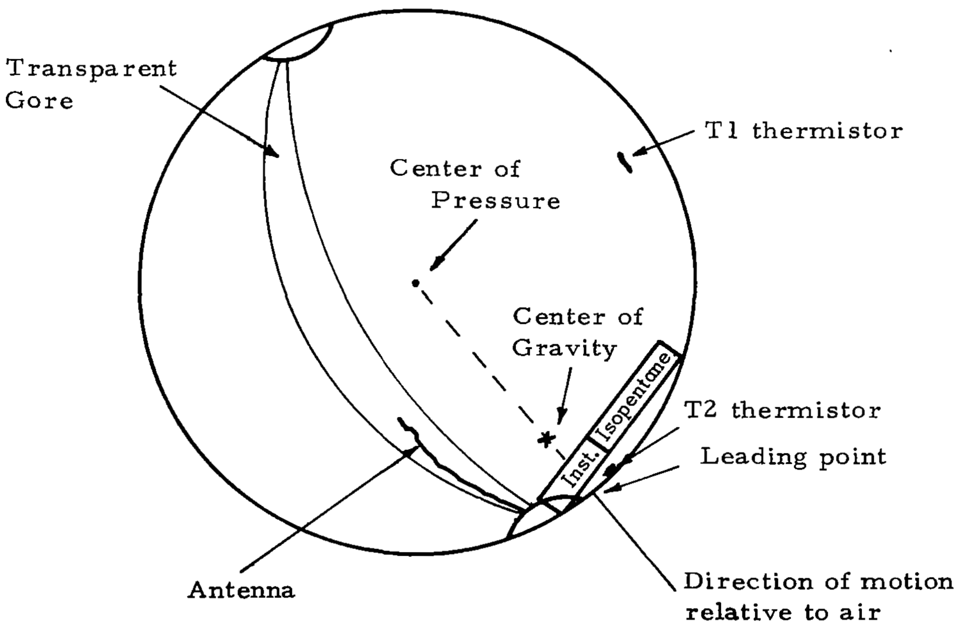

Figure 7. Instrumentation and Antenna Location

To instrument the Super Loki system a different packaging procedure would be used. The Super Loki system, unlike the Viper dart system, contains a pyrotechnic delay mechanism designed to retard isopentane vaporization of the sphere for several seconds after ejection. Since the delay mechanism does not appear necessary it could be removed from the capsule and replaced with the electronics and sensor package. This exchange would keep the mass of the system at approximately its present value of 165 grams.

SECTION 3
PRESSURE

The measurement of internal sphere pressure can be used to assess the structural integrity of the sphere. The inflation capsule inside the sphere contains sufficient isopentane to inflate the sphere to 10 mb pressure. Under this pressure sphere collapse should occur at approximately 30 Km. A monitor of internal pressure would determine if the isopentane vaporizes completely and under what time frame this occurs. Should pinhole leaks occur in the sphere a slow rate of internal decrease in pressure will be observed. If pressure buildup at Mach 1 tends to distort the shape of the sphere this event can be observed through a corresponding increase in internal pressure. Finally an internal pressure sensor could accurately pinpoint the collapse altitude of the sphere -- a long disputed problem. When internal pressure increases above the 10 mb level then sphere collapse is certain, and internal pressure equals external pressure. After collapse the internal pressure sensor measures atmospheric pressure which extends downward the altitude range for meteorological measurement.

An alternate means of monitoring internal sphere pressure would be through the use of a differential pressure transducer. Physically the difference between an absolute and differential pressure transducer is that the absolute transducer has a sealed tube at reference pressure while the differential transducer has the tube vented to the exterior. By mounting a differential transducer on the skin with the reference tube vented to the exterior of the balloon the difference in pressure between the balloon interior and the ambient pressure can be monitored. Since at altitudes above 60 Km the ambient pressure is very small compared to the internal pressure, the differential can be used as an excellent approximation to the internal pressure. At lower altitudes the ambient pressure, as measured by the integration of the drag determined density, can be added to the pressure differential to determine internal sphere pressure. There are both advantages and disadvantages to the utilization of a differential pressure transducer. The disadvantages are: a) The pressure distribution around the sphere is not the ambient pressure -- particularly at high Mach number. Thus the differential pressure measurement would reflect the pressure buildup relative to the point on the sphere at which the reference pressure tube protrudes. This does not seem to be a serious problem however for two reasons: the density is so small at high altitudes when the velocity is large that the dynamic pressure at any point on the sphere is negligible as compared to the internal pressure and; secondly, as will be shown later, the sphere will orient itself so that the line connecting the center of mass with the center of the sphere will align itself with the velocity vector. Thus the transducer orientation will be known and pressure build-up can be compensated for. A second disadvantage (b) of the differential transducer is its inability to measure ambient atmospheric pressure after collapse. The differential pressure goes to zero when the sphere collapses and remains at zero thereafter.

A differential pressure transducer has some important advantages. A differential transducer will sensitively monitor, by a drop in differential pressure, any forces exerted on the sphere when it passes through Mach 1. The most important advantage however, for the differential transducer is its ease in calibrating. Since pressure transducers must be calibrated for zero shift and temperature dependence this can be accomplished for differential transducers at near atmospheric background pressures. For absolute pressure transducers evacuation of a pressure chamber to 100 Km altitude and stringent temperature control would be required.

The range of calibration required for a transducer attached to the skin of a sphere cannot be determined at this time. The temperature of the skin to which the transducer is attached is an unknown variable. Depending upon altitude, time of day, and albedo, the range of skin temperatures could conceivably vary as much as 150°C. The pressure transducer must be calibrated to compensate for the temperature variability. Until more is known concerning the temperatures experienced by the transducer the calibration range will have to be assumed. The launching of a few experimental instrument systems should determine a nominal range of temperatures. A preflight calibration can be made to compensate for these anticipated temperatures. For an operational type system the calibration of the transducer would occur during the manufacturing or assembly process. At that time each transducer would be calibrated versus temperature and the calibration chart would accompany the instrument package.

3.1 SENSOR REQUIREMENTS

A miniaturized pressure transducer to monitor internal sphere pressure or pressure differential subject to the constraints of launching, the extreme atmospheric temperature range, and the low pressure for which measurements are needed provides a state of the art challenge to miniaturization technology. The important performance properties that a pressure transducer must possess are:

1) Measurement range 0-15 mb (absolute or differential)
2) Accuracy $\pm$ 1 mb
3) Maximum pressure to withstand 1000 mb (atmospheric)
4) Maximum acceleration to withstand 150 g (at launch)
5) Operating temperature range - 60°C to +30°C

6) Overall dimensions of transducer less than 1.27 cm on each side

No pressure transducer has been found that completely satisfies these six requirements. One of the more promising miniaturized absolute transducers is CQH-125-5 made by Kulite Semiconductor Products Incorporated. It is small, weighs less than 1 gram and if packaged cross axis to the launch load will withstand 150 g launch acceleration. It has a rated pressure of 5 P.S.I. ($\approx$ 330 mb) and will withstand a maximum pressure of 20 P.S.I. which exceeds atmospheric pressure. A zero balance shift of $\pm$ 17 mb and non-linearity response of $\pm$ 2 mb can be compensated for by pre-flight calibration. Repeatability of the instrument is well within 1 mb and thus quite satisfactory. The operating temperature range of the transducer is -20°C to $+120^{\circ}$C with temperature compensation between 25°C and 80°C. The manufacturer states that the operating range should be extendable to -60°C but temperature calibration would be required. The change of no-load output with temperature is $\pm$ 10 mb per 44°C. Since the compensated temperature range is over 80° warmer than the most severe environmental temperature a $\pm$ 20 mb correction could be needed. To calibrate for the zero balance, nonlinearity, and no-load temperature correction an exhaustive series of pre-flight tests would be required for each transducer. A millivolt output versus pressure curve would have to be generated for various temperatures at the very low 1-10 mb measurement range of interest to the experiment. Such a test schedule would require an extremely high vacuum chamber with excellent temperature control capabilities. It would be costly and not practical except on a few experimental firings. In addition, for each launch a thermistor would be needed to monitor the temperature of the pressure transducer so that the correct calibration curve could be utilized.

A differential pressure transducer analogous to CQH-125-5 can be derated to measure the differential in pressure on a 0-15 mb pressure range. The temperature sensitivity to a 0-15 mb full scale range would remain within the 1 mb tolerance. Zero balance shifts and non-linearity deviations would also be within 1 mb. Thus the differential transducer may not require the stringent calibration needed for an absolute transducer. Even if calibration of the differential transducer is needed it becomes a much simplified problem. The calibration need not be made under extreme vacuum conditions. The reference probe of a differential transducer can be vented to the atmosphere which would then only require 15 mb evacuation of a pr essure chamber to calibrate the transducer.

3.2 CIRCUITRY

The circuit diagram for a pressure transducer would be similar to the thermistor circuits with the changes shown in Figure 8. The circuit used by a thermistor to modulate the pulse spacing would be changed to a modulation of pulse spacing by the amplified output of a pressure transducer. The other thermistor would be retained to monitor the temperature of the pressure transducer. These modifications would increase the ma ss of the instrumentation package by less than 5 grams. The cost would be increased by approximately $400 (1974 prices) -- the cost of the pressure transducer and an amplifier.

3.3 PACKAGING

The differential transducer can be mounted on one of the six fiberglass boards shown in Figure 6. The mounting will be aligned in such a way that when the sphere is packaged within the dart the sensitive axis of the transducer will be perpendicular to the g-force direction of launch. The reference tube from the transducer will be vented through the skin of the sphere to the atmosphere.

Other than these modifications, packaging of the pressure measurement hardware will be the same as that for temperature sensing.

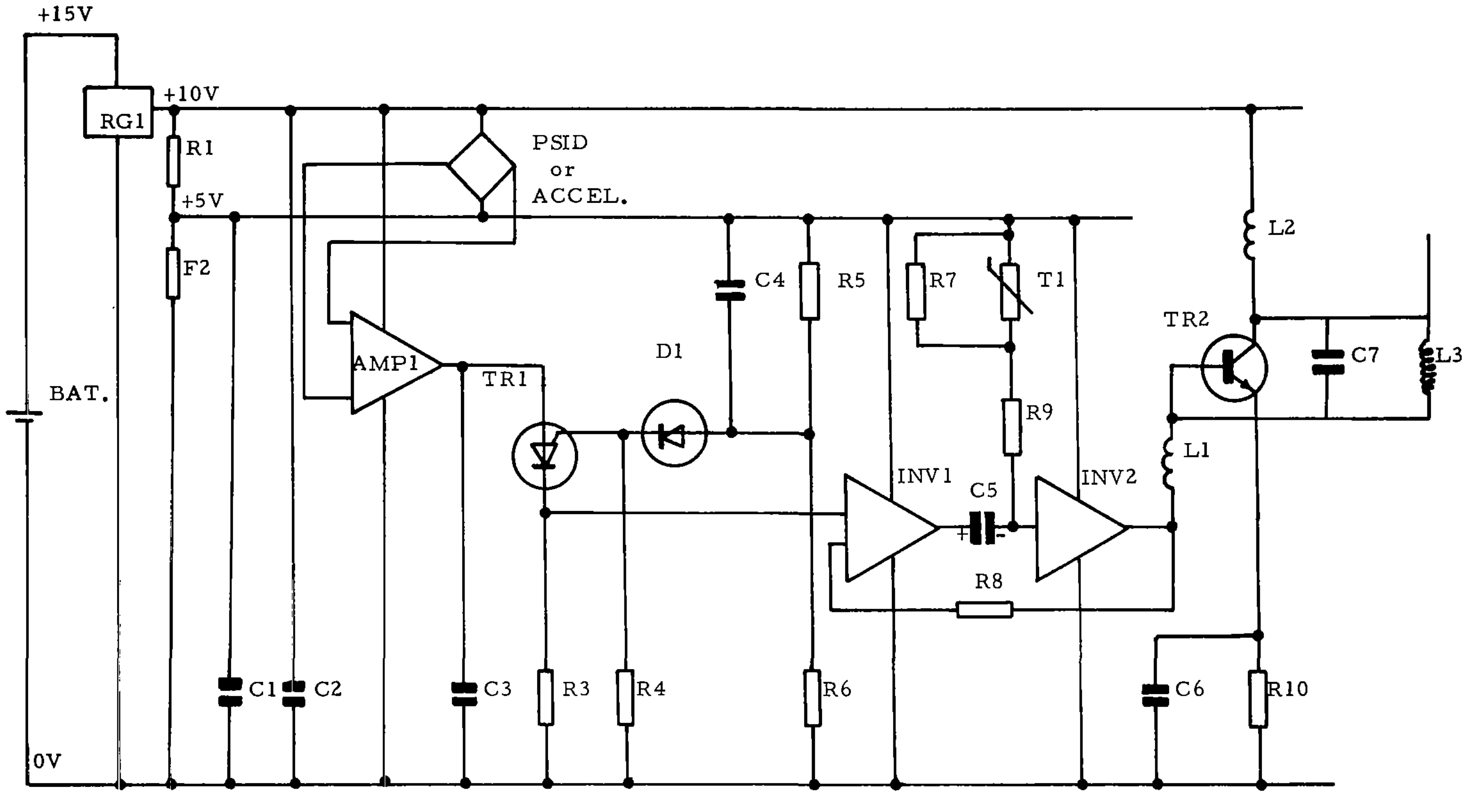

Figure 8. Circuit Diagram for a Pressure and Temperature Measurement

SECTION 4

ACCELERATION

The direct measurement of acceleration by on-board accelerometers has been done in the past with large inflatable spheres by Morrissey and Faucher, and in small solid spheres by Champion and Faire. Each sphere system contained tri-axial accelerometers positioned as near as possible to the center of mass of the sphere. In order to derive density from the three components of acceleration the direction of the velocity vector of the sphere relative to the wind was required. Because of the heavy mass of both of these systems a vertical direction could be assumed as the direction of the relative velocity vector. This assumption is not valid when discussing the light weight sphere. The inflatable sphere is a very good wind sensor and the direction of the relative velocity vector is often more attuned to the wind direction than to the vertical. In addition, for the inflatable sphere the accelerometers cannot be mounted at the center of mass because of the weight and packaging problems associated with a strut. Thus to directly measure acceleration, the accelerometers would have to be attached to the skin, and in addition some type of tracking capability would be required in order to calculate the direction of the relative velocity vector of the sphere. These requirements do not present the severe constraints one might anticipate and in fact may reduce the requirement from a tri-axial to a single axis accelerometer. Consider a sphere with a single axis accelerometer affixed to the skin as shown in Figure 9. The axis of the accelerometer is aligned along the line connecting the center of mass of the sphere to its center of pressure (center of sphere). Since the accelerometer is falling with the system it will not observe the gravitational force. It will measure only drag and buoyancy forces, the latter of which is negligible at altitudes above 30 Km. The drag force acts about the center of pressure of the sphere and in a direction opposite to that of the velocity vector relative to the wind. Since the center of mass is not at the center of pres-

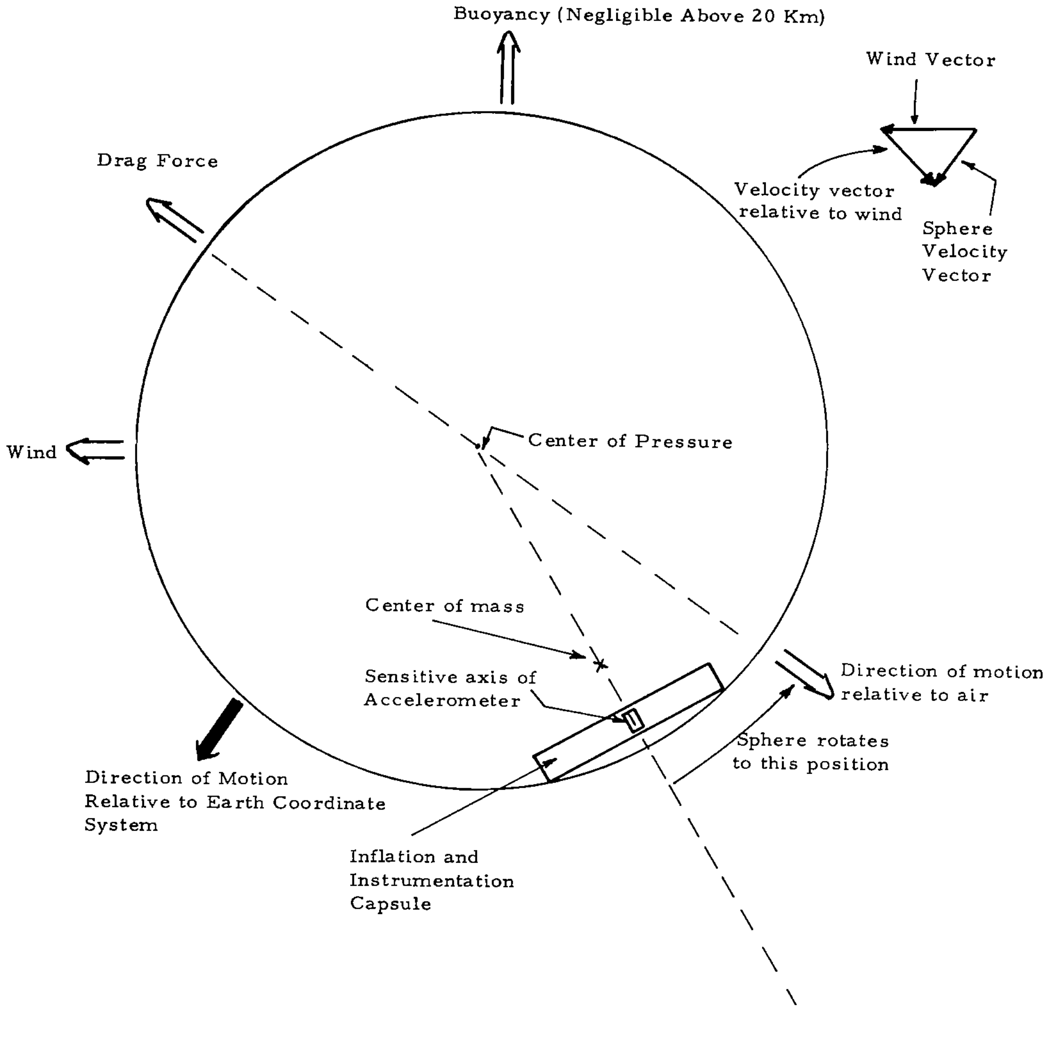

Figure 9. Forces Exerted on Sphere and Orientation

sure the force exerted at the center of pressure will rotate the sphere until the center of mass aligns itself along the drag force line. At this point the axis of the accelerometer will be aligned with the relative velocity. The deceleration observed by the accelerometer is the total drag deceleration of the sphere. Only its direction must be known to enable density calculations. The direction of the drag force vector could presumably be derived with sufficient accuracy with GMD-4 or DOVAP type tracking equipment. Presently high precision FPS-16 radars are needed to derive density from the passive sphere. It therefore appears possible to obtain density at least under steady state conditions, by means of a single axis accelerometer. However dynamic motions of the sphere must also be analyzed. In an actual launch situation the sphere, at ejection, is spinning or wobbling about its center of mass due to the initial spin imparted from the rocket. If the sphere is not rotating about the axis connecting the center of pressure to the center of mass then it is wobbling and this wobbling can only be damped by the drag force. The mounting of a single axis accelerometer near the skin would monitor a cyclic acceleration trace due to the drag force. From the observed frequencies one could deduce the orientation and spin behavior of the sphere and the restoring time needed for the sphere to align itself in the equilibrium position.

An additional use for an acceleration trace would be for comparison with radar derived acceleration coordinates. Agreement between accelerometer and radar derived accelerations in small scale detail would validate the density and temperature oscillations observed in the reduced Robin meteorological data. If agreement were not found improved data reduction procedures would need to be derived.

4.1 SENSOR REQUIREMENTS

For a single axis accelerometer to provide the data needed to justify its incorporation into the passive sphere system the following requirements on the part of the accelerometer must be met.

1) Measurement accuracy of 0.2g.

2) Measurement range of 0-5g.

3) Dimensions less than 1.27 cm on each side

4) Time constant less than 1 second

5) Operating temperature range of $-60^{\circ}C$ to $+30^{\circ}C$

6) Maximum acceleration to withstand 150g (at launch)

Miniaturized accelerometers are available that successfully meet all of these requirements.

Several accelerometers have been found with dimensions less than .3 inches and mass less than 1/2 gram. These accelerometers generally only have an operating temperature range to $-40^{\circ}C$. This can be extended to operate in a $-60^{\circ}C$ environment by embedding the accelerometers in an insulating material. The zero output accuracy of the accelerometers is $\approx 0.3g$. In flight calibration for zero output is easily achieved due to the low density atmosphere into which the sphere is initially ejected. Above 100 Km the sphere will experience no significant deceleration which will allow a zero output calibration to be made. Thermal sensitivity of the accelerometers is less than $.2^{\circ}$ per $100^{\circ}C$ when operating outside the compensated temperature range. This can be controlled by calibration or by choosing a compensated temperature range within the anticipated temperature variability of the environment. To withstand the 150g launch acceleration the accelerometer can be packaged with its sensitive axis perpendicular to the direction of the launch force acceleration. If the sensitive axis of the sphere is packaged in this direction the spin of the dart must also be considered. The dart spin will produce an acceleration that will be measured by the accelerometer and will depend upon the distance of the accelerometer from the spin axis of the dart. Assuming a maximum rotational velocity of the dart of 40 revolutions per second and an accelerometer capable of withstanding a 20g acceleration the allowable distance of the accelerometer from the axis of rotational is determined from the equation:

$$r = \frac{a}{\omega^2}$$

where:

r is the distance of the accelerometer from the axis of rotation

a is the acceleration measured by the accelerometer

ω is the frequency of rotation of the dart

Solving for r gives a distance of 0.3 cm as the maximum distance of the accelerometer from the spin axis of the dart. If a representative value for the rotational velocity of the dart, say 25 revolutions per second is used instead of the maximum value, the allowable distance from the spin axis increases to 0.8 cm. The accelerometer can be positioned within this tolerance.

4.2 CIRCUITRY

The circuit diagram needed to obtain a single axis accelerometer and a temperature measurement would be identical to that described for a pressure and temperature measurement. The only difference would be the replacement of the pressure transducer in the pressure circuit with an accelerometer. The mass of the system would be virtually unchanged. The cost of an accelerometer is \$225 as compared to \$365 for a pressure transducer (1974 prices).

4.3 PACKAGING

Proper orientation of the axis of the accelerometer is important both during launch and during its sensing lifetime. The sensitive axis of the accelerometer must coincide with a line connecting the center of mass of the sphere system with its center of pressure (see Figure 10). This can be achieved by placing the accelerometer in the proper location in the capsule and rigidly attaching the capsule to the sphere skin. The canister must be attached or supported so that no rolling motion of the canister can occur. The axis of the accelerometer will be perpendicular or nearly perpendicular to the long-

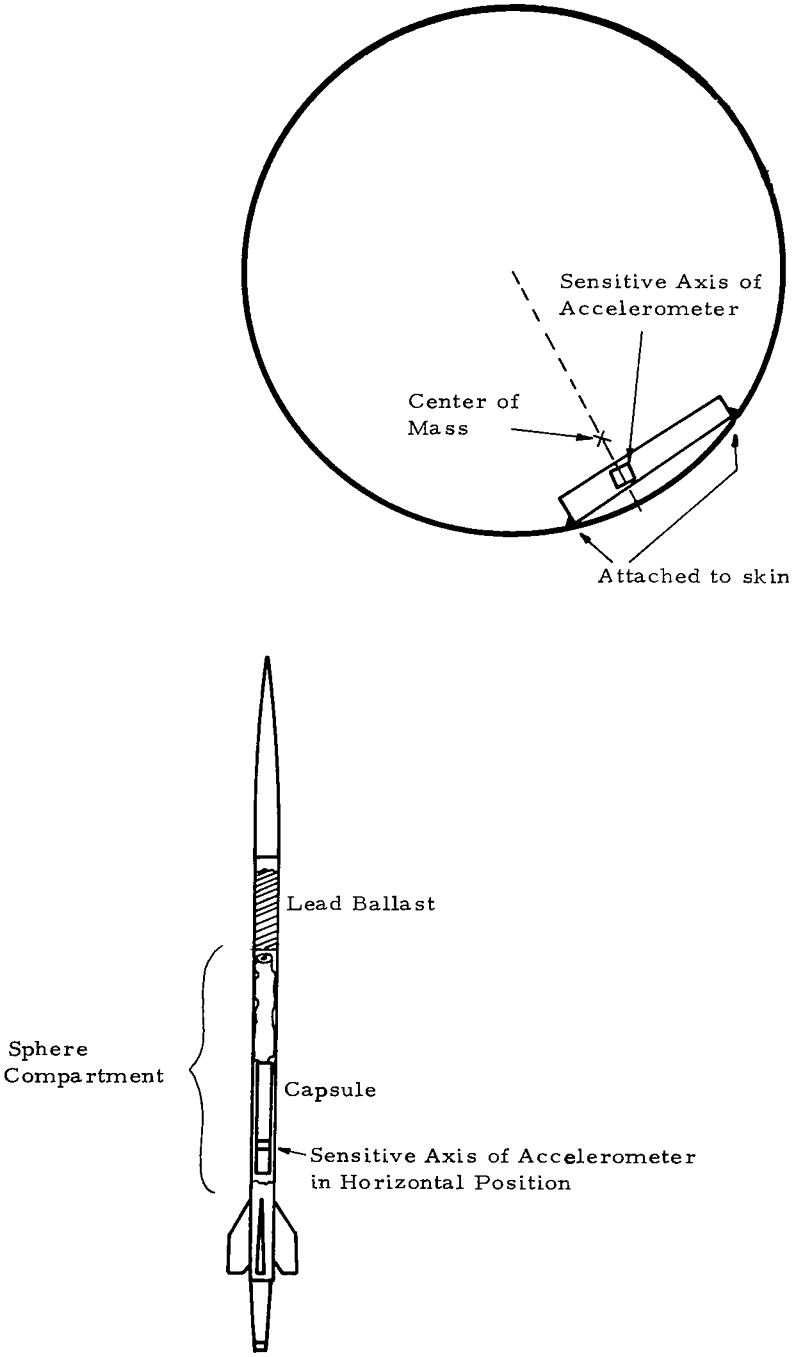

Figure 10. Orientation of Accelerometer at Launch and with Sphere Inflated

itudinal axis of the capsule. In packaging the capsule inside the dart the sensitive axis of the accelerometer will be in a horizontal position and will withstand the launch forces.

SECTION 5
SUMMARY AND RECOMMENDATIONS

The feasibility of instrumenting the Robin sphere with miniaturized thermistors, pressure transducers and accelerometers has been studied and it appears practical to proceed with an experimental test program. The practicality of skin temperature measurements has already been established with the Australian 2-meter sphere system and presents no particular difficulties in adapting to the Robin system. Since skin temperature is perhaps the most important of the three parameters higher priority should be allotted toward incorporating it into the Robin system. Skin temperature measurements could potentially be used to calculate temperature, pressure, density, and vertical winds from 90 through 30 Km.

A pressure measurement would primarily be used as a diagnostic tool in monitoring the inflation-collapse behavior of the sphere. It has little chance for incorporation into an operational system. The technical feasibility of a miniaturized pressure transducer accurately monitoring internal sphere pressure has not been completely established. It does however appear justified in pursuing at least on a limited experimental basis. Its need, potential and cost however do not warrant the emphasis in a developmental program that should be given the temperature measurement.

The technical feasibility for obtaining an acceleration measurement appears quite favorable. The application of the acceleration measurement however may be limited if the orientation of the sphere is not sufficiently stable to produce a steady state acceleration trace. If the total drag acceleration can be accurately deduced from the acceleration profile generated by a single axis accelerometer then an important breakthrough may follow which would permit the passive sphere system to be flown at locations not possessing an FPS-16 radar. Thus the potential benefits from an accelerometer equipped sphere warrants an experimental test and development program.

An initial flight test of six instrumented systems is recommended. Each system should be equipped with two sensors to transmit two channels of information. The six systems should be instrumented or flown in the following order:

1) two thermistors on skin

2) two thermistors on skin (different location from 1)

3) pressure transducer and thermistor to measure temperature of transducer

4) pressure transducer and thermistor to measure temperature of transducer

5) thermistor on skin and accelerometer

6) thermistor on skin (different location) and accelerometer

The successful flight test of these six systems should provide ample data to assess the potential of improved falling sphere systems that incorporate direct measurements of one or more of the parameters, temperature, pressure and acceleration.

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